

VARIATION OF BURNING VELOCITY
OF LAMINAR FLAMES WITH PRESSURE
BY THE BURNER-AREA METHOD

John M. Charles



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CHARLES

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THESIS
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Letter on front cover:

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Pasadena, California

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Thesis by

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Lieutenant, United States Navy

In Partial Fulfillment of the Requirements

For the Degree of

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SUMMARY

Because of the disagreement in the published data on the effect of pressure on the burning velocity of laminar flames a general study was undertaken at the California Institute of Technology Jet Propulsion Laboratory to determine the variation of burning velocity with pressure by the burner-area method. This report is a portion of that study.

The mixtures utilized for this investigation were ethylene-air, isobutylene-air, propylene-oxygen-nitrogen, and propylene-air. Expressing the pressure dependence of burning velocity as p^n , the value found for n is -0.13 for ethylene-air, -0.186 for isobutylene-air, -0.153 for propylene-oxygen-nitrogen, and -0.132 for propylene-air. The results compare reasonably well with the experimental findings of Pardee,⁽¹⁰⁾ Cullen,⁽⁶⁾ and Culshaw and Garside.⁽⁵⁾ At atmospheric pressure the values of burning velocity of the mixtures studied in this report are in close agreement with several experimental investigators.

Also investigated was the effect on the burning velocity of a mixture of acetylene-oxygen with the addition of helium. The trend found is that the burning velocity of an acetylene-oxygen mixture increases with the addition of helium up to a maximum at a certain percentage of helium and then decreases as more helium is added.

TABLE OF CONTENTS

PART	TITLE	PAGE
	Acknowledgements	i
	Summary	ii
	Table of Contents	iii
I.	INTRODUCTION	1
II.	EQUIPMENT	4
III.	EXPERIMENTAL METHOD AND PROCEDURE	9
IV.	DISCUSSION OF RESULTS	15
	References	25
	Figures	27

I. INTRODUCTION

Burning velocity of a laminar flame is defined as its linear velocity, normal to the flame front, relative to the velocity of the unburned gas entering the combustion zone. The flame front is the thin layer distinguished by a rapid chemical reaction, the evolution of heat, and is generally accompanied by luminosity.

The laminar burning velocity of a combustible mixture is dependent on the physical properties or state of the gaseous mixture, the transport properties, and the reaction kinetics. The manner in which the burning velocity varies with pressure can be estimated from the way in which pressure affects the foregoing factors. One of the factors appreciably affected by pressure is the diffusion coefficient which varies inversely as the pressure. It is observed, however, that the diffusion coefficient enters into the burning velocity relations only through the ratio of the Schmidt number to the Prandtl number which is independent of pressure. The major effect of pressure on the laminar burning velocity appears to be through the rate of governing reactions, the form of which indicates the quantitative way in which pressure enters into the concentration functions. As pointed out in the theories of J. F. Boys and J. Corner⁽¹⁾ and J. O. Hirschfelder and C. F. Curtiss,⁽²⁾ the laminar mass burning velocity M of a flame controlled by a chemical reaction of order n can be shown to be proportional to $p^{n/2}$. From the continuity equation for constant pressure deflagration it follows that the laminar burning velocity U_0 is proportional to $p^{n-2/2}$. This relation indicates that the laminar burning velocity is proportional to $p^{-0.5}$ for a unimolecular reaction ($n=1$), p^0 for a bimolecular or second order reaction ($n=2$), and $p^{-0.25}$ for a three halves order reaction ($n=3/2$).

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The results appearing in this report indicate the probable bimolecular character of the flames studied.

This study of the rate of flame propagation is of practical interest because of its importance in the field of jet propulsion. It has been observed that a correlation exists between the combustion efficiency of a ram jet burner and the laminar burning velocity of the fuel. The effect of pressure on the propagation rate of flames in jet combustion chambers, particularly at high altitude conditions, is also of growing importance. Modern aircraft are requiring higher velocity combustion as airspeed increases; thus, the burning velocity of all likely fuels should be known for the proper design and operation of aircraft and missile power plants.

This investigation is a portion of a long-term program started in 1947 which has as its objective the fundamental study of flame propagation and flame processes. Because the regime of subatmospheric pressure produces unusual extension of the flame burning zone, the studies are carried out at pressures of 1 atmosphere and below.

Contributing to this work are such experimenters as H. S. Pickering and J. W. Linnett,⁽³⁾ who conclude that burning velocity remains constant over the pressure range 200 to 760 mm Hg abs. Linnett and P. J. Wheatley,⁽⁴⁾ applying the same mixtures as Pickering and Linnett, find that the burning velocity increases as the pressure is lowered (approximately as $p^{-0.25}$). G. W. Culshaw and J. E. Garside⁽⁵⁾ reveal a dependency of burning velocity on pressure (roughly as $p^{-0.12}$). A plot of R. E. Cullen's⁽⁶⁾ data for ethylene-air shows approximately that burning velocity varies as $p^{-0.13}$.

In general, it may be summarized that some investigations indicate that burning velocity increases as pressure is lowered while others conclude that burning velocity is constant as the pressure changes. There is much disagreement on this subject depending on the method used and the fuel investigated. Thus, this study of variation of burning velocity with pressure is undertaken in order to amplify the research knowledge in this field.

An investigation has been made in this report of the change of burning velocity of an acetylene-oxygen mixture with the addition of varying amounts of helium applying two different burner sizes and two different pressures below 1 atmosphere. There is also studied the effect of pressure on the burning velocity of mixtures of ethylene air, isobutylene-air, propylene-oxygen-nitrogen, and propylene-air.

II. EQUIPMENT

The equipment for burning velocity experimentation consists of a flow system, a pressure control system, a pressure chamber, a pumping system, an igniter, and an optical system. With reference to Fig. 1 which is a diagram of the flow and pressure control systems the gases to be employed flow from the source of supply through two-stage pressure regulation to the flowrators. After passing through the flowrators, the gases are metered through long taper needle flow valves to the mixing chamber where by means of screens and baffles they are thoroughly mixed. The mixture then flows through a honeycomb filter which produces a uniform velocity of flow and suppresses disturbances created in the mixer. The gaseous mixture then passes through the duct tubing which is designed to allow the build up of a parabolic velocity profile to assure laminar flow at the burner lip. The burner-exit is located at the center of the bottom of a large pressure chamber constructed so that burning may take place at sub-atmospheric pressure without influence from the chamber walls.

The pressure in the pressure chamber is governed by means of a sensitive needle valve in the bleed system which is also shown in the diagram of Fig. 1. The bleed-control valve allows a constant leak of atmospheric air into the acoustic filter which reduces transient disturbances in the vacuum system so that flame vibration due to the pump will be minimized. The pressure in the pressure chamber is indicated by absolute pressure gages from 0 to 100 mm Hg abs and by a straight tube mercury manometer from 100 mm Hg abs to atmospheric pressure.

Included in the flow system described above is the source of gas supply. Bottle gases for which representative compositions are given in Table I were used in all cases with the exception of air which was supplied through the laboratory compressor and passed through oil and moisture filters. It was found that the composition of air in commercially supplied air bottles is unreliable. An analysis of one air bottle revealed it contained 28.8 percent oxygen.

The Fischer-Porter C-clamp calibrated Flowrators (rotameters) are mounted on the control panel and measure the volume flow of the gas. Using the manufacturer's standard calibrated flowrator charts, gas density variation, and an independent flow calibration curve obtained with a Precision Wet-Test Gas Meter, the volume flow of gas is believed to be determined within ± 2 percent limits over the range of flow required. In accordance with the standard flowrator charts all gases with the exception of isobutylene were metered to the flowrators at a pressure of 40 psia. Isobutylene was metered at 24.7 psia due to its liquid state and relatively low vapor pressure.

The pressure chamber, as shown in Figs. 2 and 3, is cylindrical in shape with an inside diameter of 24 inches and a height of 60 inches. The chamber is double-windowed with two pieces of glass in each window designed to take the required pressure load and to afford the necessary heat insulation. To resist moisture collection the windows are periodically treated with a preparation called Fogpruf made by the Mine Safety Appliance Company. The burner-duct exit is surrounded by a water jacket flush with its flat upper surface to avoid temperature variation.

The pumping system includes a Kinney Model DVD 1414813

TABLE I
Representative Composition of Commercial Bottled Gases

Acetylene %	Oxygen %	Nitrogen %	Helium %	Isobutylene %	Ethylene %	Propylene %
C_2H_2 99.62	O_2 99.7	N_2 99.5	He 100	C_4H_8 99.0	C_2H_4 99.5	C_3H_6 99.0
O_2 0.08	N_2 0.3			Butene 1	Air	C_3H_8
N_2 0.11					C_3H_8	
H_2 0.06						
H_2S 0.01						
SiH_4 0.03						
CO 0.01						
CH_4 0.04						
PH_3 0.04						
NH_3 trace						

mechanical vacuum pump as pictured in Fig. 4, remotely operated control valves, and, as mentioned before, an acoustic filter. The rated capacity of the Kinney pump at 1 mm Hg abs is about 340 cu ft/min.

An ignition flame is produced at an inverted cone positioned over the burner-exit by means of an electrical spark igniter using oxygen and acetylene.

To obtain an image of the flame seated on the burner lip a 5 inch diameter double-convex lens is mounted outside of the pressure chamber window as shown in Fig. 2. The image is erected and projected to the horizontal plane on a pedestal-mounted glass plate by a front surface plane mirror placed at 45° . A thin, translucent plastic taped over the glass plate acts as a screen for the image. The optical system is adjusted to obtain a very precise full scale image by using graduated scales as the object. In this manner a flame profile, as shown in Fig. 5, may be rapidly traced on the plastic screen. A cathetometer, as pictured in Fig. 3, is located on a steel table outside of the opposite window of the pressure chamber to accurately measure the height of the flame cone. This affords a check on the accuracy of the trace. The equipment as described above is thoroughly discussed by M. Gilbert.⁽⁷⁾

Over the pressure range of 100 mm Hg abs to atmospheric pressure the burner size needed is constantly changing. Employed in this investigation were cylindrical burner-ducts with the following diameters: 1.86, 1.25, 0.877, and 0.50 inches. To make the system more flexible long nozzle inserts of 1.60, 0.685, and 0.377 inches diameter were also used. The inserts as designed are about 1.5 diameters in length with a close-tolerance machined fit. The sides of the flame cone observed when using

the nozzle inserts appeared straighter than with the basic ducts. This indicates a slight flattening of the velocity profile of the combustible mixture flowing out of the burner-exit. The burner-ducts and nozzle inserts are pictured in Figs. 6 and 7.

III. EXPERIMENTAL METHOD AND PROCEDURE

The literature reveals that several methods of burning velocity determination have been employed. The most widely used of these seem to be the Bunsen burner method, the soap bubble method, and the tube method. The Bunsen burner method involves establishing a flame cone on a burner-duct and computing the burning velocity from the known volume flow of gaseous mixture and the surface area of the flame front. The flow around the dead space, i. e., the vertical distance between the top of the burner lips and the base of the flame, and the rounded tip of the flame cone must be considered in the burner-area method. The possible errors related to dead space and cone tip are negligible if the cone height and gas flow are sufficiently large. The inner cone of the Bunsen flame, chosen at the onset of luminosity in this work, has been located by visual means, direct, Schlieren, and shadow photography. In accordance with H. R. Conan and Linnett,⁽⁸⁾ the cones thus ascertained do not generally coincide. Thus, the value of burning velocity will vary with the particular inner cone used. Also the thickness of the luminous flame zone increases as pressure is lowered. The location of the inner cone may account for some of the variation of burning velocity reported by the many experimenters in this field. A comparison of the results of this report with those of other investigators, however, seems to indicate that the particular method used to locate the inner cone does not appear to have a significant effect on the computed values of burning velocity.

In the soap bubble method the combustible mixture to be investigated is used to inflate a soap bubble and it is then ignited centrally. The

rate of travel of the flame is obtained from timed photographs. This method is limited because the gas must always be saturated with water vapor. The values of burning velocity obtained in this work agree reasonably well with those of the soap bubble method.

The tube method involves a tube, a few inches in diameter and 5 to 6 feet long, closed at one end, and filled with the combustible mixture. The gas is ignited at the open end, and the rate of travel is measured directly, either photographically or electrically. Various undesirable wall effects are introduced with this method. Again, it is of interest to note that the results of this report are in close agreement with those of the tube method.

It thus appears that under suitable experimental conditions the special variations introduced by the different methods indicated do not generally produce great variation in the measured burning velocities. However, because of occasional cases of marked disagreement between methods, the reliability of experimental results is strengthened when agreement between widely different techniques is observed.

The Bunsen burner-area method was chosen for this investigation because it is believed adequate to give the variation of burning velocity with pressure and will show reasonable accuracy in the value of burning velocity when compared with other experimenters. As demonstrated by G. A. Eriksen⁽⁹⁾ and W. M. Pardee,⁽¹⁰⁾ the burner-area method with the experimental setup as used in this report results in data which is reproducible within about ± 2 percent. The source of most errors is due to inaccuracies in measurement of the surface area of the flame cone, the flowrator readings, the pressure readings, and in the

trace of the flame profile.

The burner method employing a visual cone-area procedure for investigating the burning velocity at a constant mixture ratio over a range of pressure from about 100 mm Hg abs to 1 atmosphere is essentially the same as that used by Gilbert,⁽⁷⁾ Eriksen,⁽⁹⁾ and Pardee.⁽¹⁰⁾ After setting the required pressure of the desired gases upstream of the flowrators and then regulating the chamber pressure to about 25 mm Hg abs, the ignition flame is produced. Then the combustible mixture is allowed to flow, ignited, and a stable flame is seated on the burner lip. The ignition flame is then extinguished. This sequence of ignition and seating the flame is described quite clearly by photography in Gilbert's report. A typical flame seated on a typical burner-duct is indicated in Fig. 8.

The pressure is now increased in the pressure chamber, and a stable flame cone is maintained by proper regulation of the flow of gases. After the desired pressure is reached, the flowrators are accurately adjusted in accordance with a previously prepared table of flows required for the given mixture ratio. The flow rate used at a given pressure is that which gives the largest stable cone. The mixture ratio near the maximum burning velocity is employed so that the lowest possible pressure may be reached with a given burner size without blowoff of the flame. When conditions of steady state have been reached, the flame profile is traced. The cathetometer measures the height of the flame cone, not including the distance between the burner lip and the base of the flame cone. Pressure in the chamber and flowrator readings are recorded. This procedure is repeated over variable pressure increments

using the different sizes of burners until the complete pressure range is satisfactorily investigated. The need for several burner sizes in order to cover the required pressure range is due partially to quenching. Quenching is one of the factors influencing the rate of flame propagation which is attributed to the experimental system in which the burning takes place. This phenomenon of quenching experienced when employing the burner method has been previously pointed out by B. Lewis and G. von Elbe, ⁽¹¹⁾ Cullen, ⁽⁶⁾ Gilbert, ⁽⁷⁾ Eriksen, ⁽⁹⁾, and Pardee. ⁽¹⁰⁾ The effects of quenching are to reduce the burning velocity below the value expected, particularly under the conditions of low pressure, small gas flows, and small burner ducts. It is believed that the relatively cool duct rim acts as a sink for heat and probably for chain carriers due to the adsorption of atoms and free radicals. Consequently, the temperature gradient in advance of the flame front about the base of the flame cone and the temperature of the burned gases in the reaction are altered.

Each run as described above furnishes the necessary data to calculate the burning velocity utilizing a given burner size at a given pressure. Following the Gouy total area method, ^(11, 12, 13) the surface area of the flame cone is found approximating the area of the apex by a hemisphere and the surface below the tip with frustums of a right circular cone. The Gouy method has obvious advantages when dealing with flame surfaces that vary considerably from the form of a cone due to the need of widely varying pressures. It is known that the burning velocity over the entire surface area of the flame front is not constant, being faster near the tip of the cone and slower near the base

of the cone. There is, however, a partial cancellation of these errors so that the computed result of burning velocity is believed to be negligibly affected. A typical example of a flame cone surface area approximation is shown in Fig. 5.

Burning velocity is equal to the volume flow of the combustible gases corrected to the pressure of the chamber divided by the surface area of the flame cone. Using the flowrator readings and the flowrator calibration charts, the volume flow rate of gases is obtained at standard conditions of 70°F and 760 mm Hg abs. The inlet temperature of the gases is considered that of the ambient air which is actually reasonably constant and, for experimental purposes, close enough to 70°F.

Perfect gases are assumed, and the perfect gas relations are utilized in the reduction of data. The required relation may be derived from the equations of a perfect gas and continuity as follows:

$$\begin{aligned}
 T &= \text{constant} \\
 P_1 &= 760 \text{ mm Hg abs} \\
 V_1 &= \text{total standard volume flow rate metered} \\
 P_2 &= \text{pressure in the pressure chamber, mm Hg abs} \\
 V_2 &= \text{total volume flow rate metered at the chamber pressure} \\
 U_2 &= \text{burning velocity cm/sec} \\
 A_2 &= \text{surface area of the flame front} \\
 \text{since } V_2 &= U_2 A_2 \\
 \text{then } P_1 V_1 &= P_2 U_2 A_2 \\
 \text{and } U_2 &= \frac{V_1 P_1}{A_2 P_2} = \frac{V_1 \times 760}{A_2 P_2} \quad (1)
 \end{aligned}$$

Equation (1) is the basic relation used to reduce all data to the final parameters of burning velocity and pressure.

IV. DISCUSSION OF RESULTS

Chosen for the first investigation was the change of burning velocity of an acetylene-oxygen mixture with the addition of varying amounts of the inert diluent helium. The mixture ratio of acetylene to oxygen was maintained constant at 0.2 (1/2 stoichiometric), and the amount of helium was varied from 0 to about 50 percent of the total flow. As plotted in Fig. 9, conditions for the first series of points were with a 0.50 inch burner at a constant pressure of 45.7 mm Hg abs. It was found that the burning velocity of the acetylene-oxygen-helium mixture increased from the 0 percent helium point until it reached a somewhat flat maximum at approximately 17.5 percent helium and then decreased as the percentage helium was further increased. The same trend was apparent using a 0.377 inch insert and a higher pressure of 96.7 mm Hg abs except that the maximum of the curve shifted to the right to the vicinity of 24 percent helium. It is thus concluded that the trend is for the burning velocity of an acetylene-oxygen mixture to be increased with addition of helium up to a maximum at a certain percentage of helium and then decreased as more helium is added. The position of the maximum and the values of burning velocity depend upon the conditions of size of burner, pressure, mixture ratio, effects of quenching, and experimental equipment and procedure. These data are reproducible within ± 2 percent.

It is of interest to note that G. H. Morgan and W. R. Kane⁽¹⁴⁾ using the burner method at atmospheric pressure and at a stoichiometric mixture ratio show that the trend of burning velocity of acetylene-oxygen-helium is essentially that of this report. They obtained 903 cm/sec at

20 percent helium and 732 cm/sec at 40 percent helium. These results were secured utilizing a 0.1875 inch burner. They conclude that the size of the burner has a relatively large influence on the values of burning velocity observed with the helium mixture. They also indicate that although no points could be obtained with less than 20 percent diluent, there was some evidence that lower percentages of helium may cause a slightly higher burning velocity than that observed without any diluent.

H. R. Poorman⁽¹⁵⁾ also used the burner method at atmospheric pressure with a 0.070 inch burner. At a 1/2 stoichiometric mixture ratio, he found the same trend of increase of the acetylene oxygen-helium burning velocity to a maximum at about 34 percent helium and then a decrease of burning velocity as more helium was added. The values obtained are different due perhaps to the different experimental conditions.

Figure 10 is a plot of the data obtained for the second investigation, that of burning velocity versus pressure of an ethylene-air mixture at a constant mixture ratio of 0.0846. To cover the desired pressure range the 1.25, 0.877, and 0.50 inch burner-ducts and 1.00, 0.685, and 0.377 inch inserts were employed. The data derived from each size burner resulted in a curve over a portion of the total pressure range. For each burner the effect of quenching due to burner size was apparent in that it was observed that the burning velocity decreased relatively rapidly as the pressure was reduced beyond a critical point. The inverse effect of quenching with burner size was also observed. Thus, the smaller the burner size, the higher is the pressure at which the burning velocity drops off due to quenching. Accordingly the envelope

of these individual burner curves over a wide pressure range is considered to be the locus of points indicating the burning velocity of a combustible mixture unaffected by any influence from the burner itself. The slope of the envelope for ethylene-air shows that the burning velocity varies as $p^{-0.13}$. At atmospheric pressure the value of the burning velocity is 66.2 cm/sec since atmospheric pressure at the geographical location of this experiment is about 730 mm Hg abs.

There is an abundance of data in the literature concerning mixtures of ethylene-air, some of which is shown in Fig. 10. In particular, there is indicated the envelope obtained by Cullen⁽⁶⁾ with a mixture ratio of 0.0865. The envelope slope is the same ($p^{-0.13}$), but the values of burning velocity are lower than those of this report. In view of the agreement in slope the magnitude difference is of some concern. Since the burner-area method with direct photography was used by Cullen, the question that arises is whether the photographic luminous boundary and the visual luminous boundary can be significantly different to account for the discrepancy. One pertinent fact is that the human eye is much more sensitive to luminosity gradients, especially at threshold values, than the photographic plate. This is abundantly demonstrated by the fact that different observers tracing the luminous front almost always agree to the extent that the flame traces are practically coincident.

The atmospheric pressure data of this report compare very closely with the results obtained by several other investigators. The following comparisons are at atmospheric pressure and a mixture ratio of 0.0846. Conan and Linnett⁽⁸⁾ applying Schlieren photography to determine the burning velocities by the burner method state that an

ethylene-air mixture with a burner size of 1 cm diameter gave a burning velocity of 68.2 cm/sec. Pickering and Linnett⁽³⁾ using the soap bubble method with Schlieren photography found the burning velocity was approximately 66.8 cm/sec. M. Gerstein, O. Levine, and E. L. Wong⁽¹⁶⁾ determined burning velocities by a revised tube method finding the value for ethylene-air to be 66.5 cm/sec. Linnett and M. F. Hoare⁽¹⁷⁾ using the burner method with shadow photography and a burner size of 1.08 cm ascertained the value to be about 71 cm/sec. Gerstein comments that Linnett and Hoare's data are about 3 cm/sec greater than his for mixtures containing less hydrocarbon than that required for maximum burning velocity. The larger deviation for mixtures containing excess hydrocarbons he explains by dilution of the Bunsen burner flame by external air which would result in higher burning velocities for such mixtures. Dilution by external air is, of course, not possible by the revised tube method. G. L. Dugger and D. M. Simon⁽¹⁸⁾ give the experimental value for the burning velocity of ethylene-air as 63.8 cm/sec. J. M. Singer⁽¹⁹⁾ gives his result as approximately 66 cm/sec using the burner method with a rectangular duct (1.58 x 0.483 cm). He indicates that the burning velocity for a cylindrical burner of 0.944 cm diameter is about 76 cm/sec under the same conditions. Singer states that his experiments show that the curvature produced by cylindrical tubes of diameter of 1 cm or more has a measurable effect on the burning velocity and that theoretically concave curvature of the combustion surface may generally be expected to increase the burning velocity. The concave surface of a flame attached to the cylindrical burner surface supplies

more heat and free radicals per unit element back to the unburned gas than in the planar case. Since the cylindrical burner data of this report agree closely with his rectangular burner data, the argument concerning curvature effects is, insofar as this report shows, left somewhat unresolved.

Culshaw and Garside⁽⁵⁾ utilizing the burner method with burner sizes of 0.64 and 1 cm diameter found the burning velocity of ethylene-air at a mixture ratio of 0.0846 to vary from about 54.5 cm/sec at 700 mm Hg abs, 58 cm/sec at 600 and 500 mm Hg abs, 61 cm/sec at 400 mm Hg abs, and 60 cm/sec at 300 mm Hg abs. When plotted as in this report, these data show that burning velocity varies roughly as $p^{-0.12}$. They also conclude that the dependence of burning velocity upon burner size arises from the existence of a region of reduced velocity around the flame base. It is believed that the values indicated by their data are really too low due to use of too small a burner which accentuates the effect of quenching.

Pickering and Linnett⁽³⁾ using the soap bubble method with Schlieren photography conclude that the burning velocity of ethylene-air remains constant over the pressure range 200 to 760 mm Hg abs. Linnett and Wheatley,⁽⁴⁾ employing the burner method, indicate that for the same mixtures as those investigated by Pickering and Linnett the burning velocity increases as the pressure is lowered (approximately as $p^{-0.25}$).

Dugger and D. D. Graab⁽²⁰⁾ using the burner method with Schlieren photography found the burning velocity of ethylene-oxygen-nitrogen mixtures with 21 percent oxygen at a temperature of 311°K

and a mixture ratio of about 0.0846 to be approximately 80 cm/sec and at 422°K to be about 125 cm/sec. This indicates the need of surrounding the burner outlet with a water jacket to maintain the temperature of the combustible mixture at approximately room temperature.

The flame produced by a mixture of isobutylene and air at a mixture ratio of 0.0387 was studied over a pressure range of 130 mm Hg abs to 1 atmosphere, and the results are plotted in Fig. 11. To obtain the burning velocity data, it was necessary to employ the 1.25 and 0.877 inch burner-ducts and the 1.50, 1.00, and 0.685 inch nozzle inserts. As with ethylene-air, the resulting curves for isobutylene-air indicate with burner size the pressure dependency of the point of departure from the "non-quenched" envelope. The slope of the envelope of the curves obtained for each burner size shows that the burning velocity plotted in cm/sec on the logarithmic graph varies as $p^{-0.186}$. At atmospheric pressure (about 730 mm Hg abs) the burning velocity of the isobutylene-air mixture as indicated by the envelope is about 36.6 cm/sec. The mixture ratio of 0.0387 was chosen after actually checking the fastest burning mixture ratio at various pressures lower than 1 atmosphere. It is desired to use a mixture ratio in the vicinity of the maximum of the curve of burning velocity versus mixture ratio. Since the rate of change of burning velocity with mixture ratio is relatively small near the maximum, the values obtained for burning velocity are not appreciably affected by possible slight errors in flow. The mixture ratio chosen was approximately 10 percent richer than stoichiometric and is near the mixture

ratio for the fastest burning flame.

The burning velocity of isobutylene-air at atmospheric pressure is compared with that found by Gerstein, Levine, and Wong⁽¹⁶⁾ using a revised tube method. They found a mixture ratio of 0.0398 resulted in a burning velocity of 37.5 cm/sec. It is believed that these results reveal a different mixture ratio for fastest burning due to the dependence of the point of maximum burning velocity on pressure.

The fourth experimental investigation was carried out with a mixture of propylene-oxygen-nitrogen. The logarithmic plot of the results of burning velocity versus pressure is as given in Fig. 12. The volume ratio of oxygen to nitrogen was held constant at 21/79, and the mixture ratio of the combustible mixture was 0.0516. Again, the constant mixture ratio was chosen about 10 percent higher than stoichiometric. The necessary burner sizes were the 1.25, 0.877, and 0.50 inch ducts and the 1.00 and 0.685 inch inserts. The burning velocity at atmospheric pressure is 44.6 cm/sec. The envelope of the individual burner curves shows that for a propylene-oxygen-nitrogen mixture the burning velocity varies as $p^{-0.153}$.

For comparison purposes, a propylene-air mixture, using the same burner sizes and the same mixture ratio as for the propylene-oxygen-nitrogen mixture, was investigated. The results are plotted in Fig. 13. The envelope of the burner curves discloses that the burning velocity of a propylene-air mixture under the stated conditions varies as $p^{-0.132}$. At atmospheric pressure the burning velocity is 46.6 cm/sec. It is of interest to observe that the small percentage of inert diluent in air apparently produces an increase of burning velocity of

about 2 percent when compared to the value obtained with propylene-oxygen-nitrogen. This increase may conform with the results of the acetylene-oxygen-helium investigation.

K. L. Gray, Linnett, and C. E. Mellish,⁽²¹⁾ using the soap bubble method with direct photography and the burner method with Schlieren photography, determined the burning velocity of a propylene-air mixture at atmospheric pressure and a mixture ratio of 0.0516 to be approximately 46.1 cm/sec for the burner method and 44 cm/sec for the soap bubble method. Gerstein, Levine, and Wong⁽¹⁶⁾ found the burning velocity of propylene-air at atmospheric pressure and a mixture ratio of 0.053 to be 43.8 cm/sec by the tube method.

A comparison of the results of this report with those of other experimental investigations is shown in Tables II and III. Considering an overall view of the results of the variation of burning velocity versus pressure of ethylene-air, isobutylene-air, propylene-oxygen-nitrogen, and propylene-air, there exists agreement in the trend of burning velocity variation with pressure with experimental investigators such as Pardee,⁽¹⁰⁾ Cullen,⁽⁶⁾ and Culshaw and Garside.⁽⁵⁾ As is commented with each investigation, the atmospheric pressure points of this report compare closely with most investigators. The results of this report are experimentally reproducible within ± 2 percent, and it is believed that the values obtained for burning velocity are conservatively accurate to ± 5 percent.

TABLE II.

Comparison of Results at Atmospheric Pressure

Combustible Mixture	Mixture Ratio	Report	Burning Velocity cm/sec
Ethylene-Air	0.0846	This Report	66.2
		Conan-Linnett ^{(8)*}	68.2
		Pickering-Linnett ⁽³⁾	66.8
		Gerstein-Levine-Wong ⁽¹⁶⁾	66.5
		Linnett-Hoare ⁽¹⁷⁾	71.0
		Dugger-Simon ⁽¹⁸⁾	63.8
		Singer ⁽¹⁹⁾	66.0
Isobutylene-Air	0.0387	This Report	36.6
	0.0398	Gerstein-Levine-Wong ⁽¹⁶⁾	37.5
Propylene-Oxygen-Nitrogen	0.0516	This Report	44.6
Propylene-Air	0.0516	This Report	46.6
	0.0516	Gray-Linnett-Mellish ⁽²¹⁾	46.1 44.0
	0.0530	Gerstein-Levine-Wong ⁽¹⁶⁾	43.8

* indicates reference number.

TABLE III

Comparison of Results of Variation of Burning
Velocity with Pressure

Combustible Mixture	Mixture Ratio	Report	Pressure Exponent
Ethylene-Air	0.0846	This Report	-0.13
	0.0865	Cullen ^{(6)*}	-0.13
	0.0846	Culshaw-Garside ⁽⁵⁾	-0.12
	- - -	Pickering-Linnett ⁽³⁾	0.0
	- - -	Linnett-Wheatley ⁽⁴⁾	-0.25
Isobutylene-Air	0.0387	This Report	-0.186
Propylene-Oxygen-Nitrogen	0.0516	This Report	-0.153
Propylene-Air	0.0516	This Report	-0.132

* indicates reference number.

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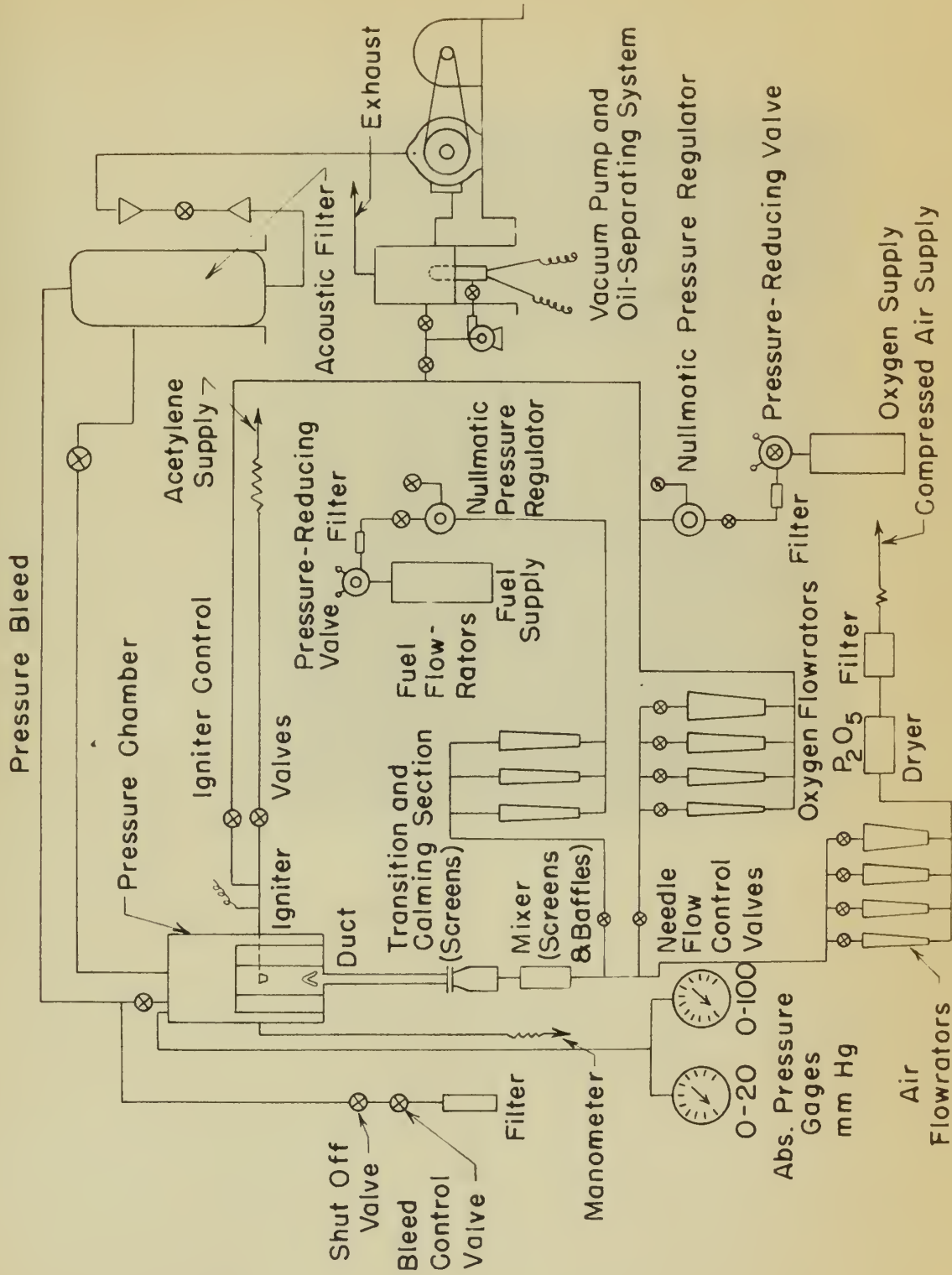


FIG. 1 - DIAGRAM OF FLOW AND PRESSURE CONTROL SYSTEMS

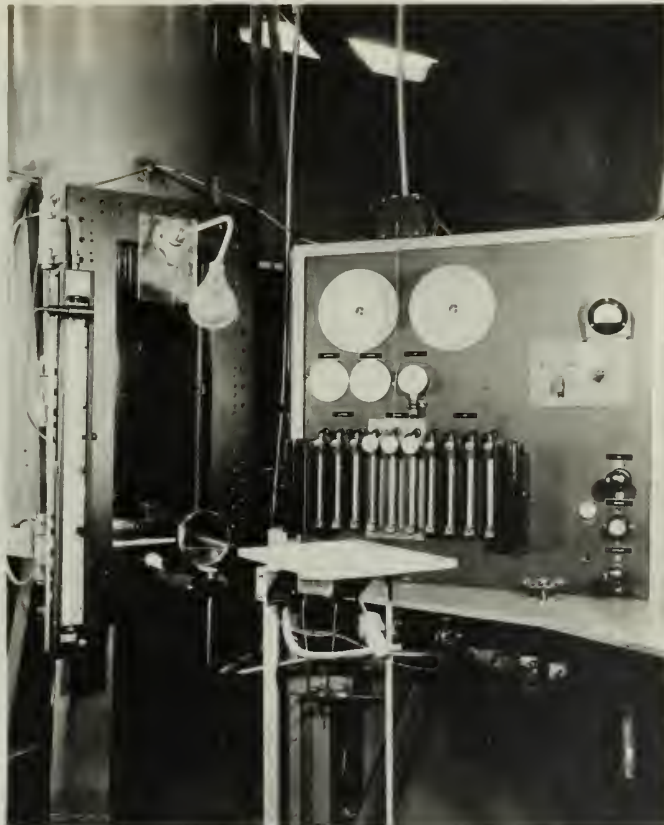


Fig. 2 PRESSURE CHAMBER, CONTROL PANEL,
AND OPTICAL SYSTEM

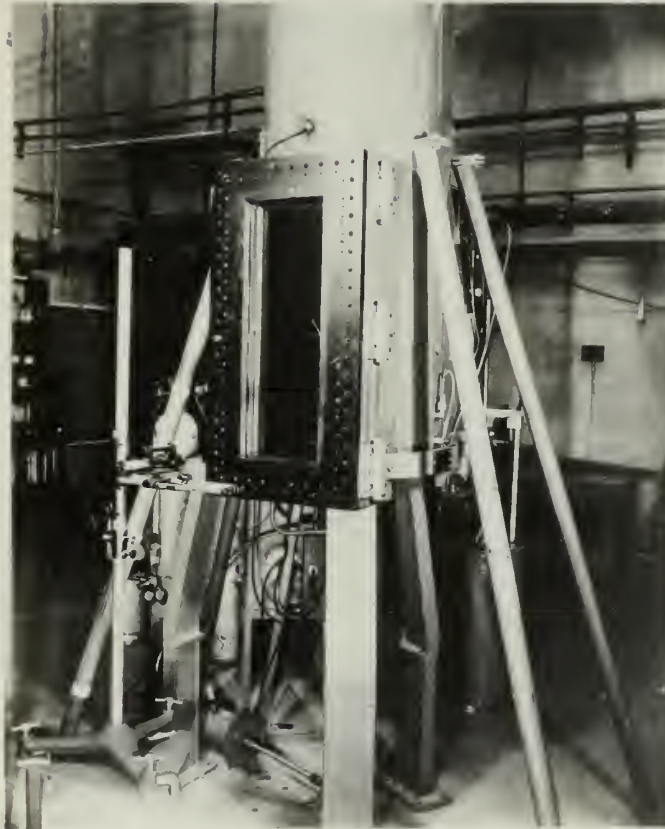


Fig. 3 PRESSURE CHAMBER AND CATHETOMETER

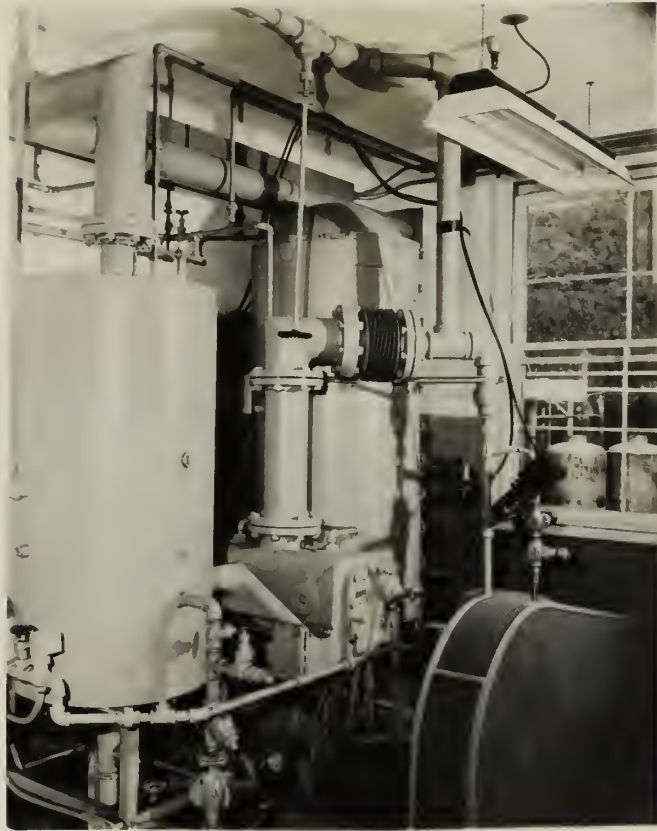
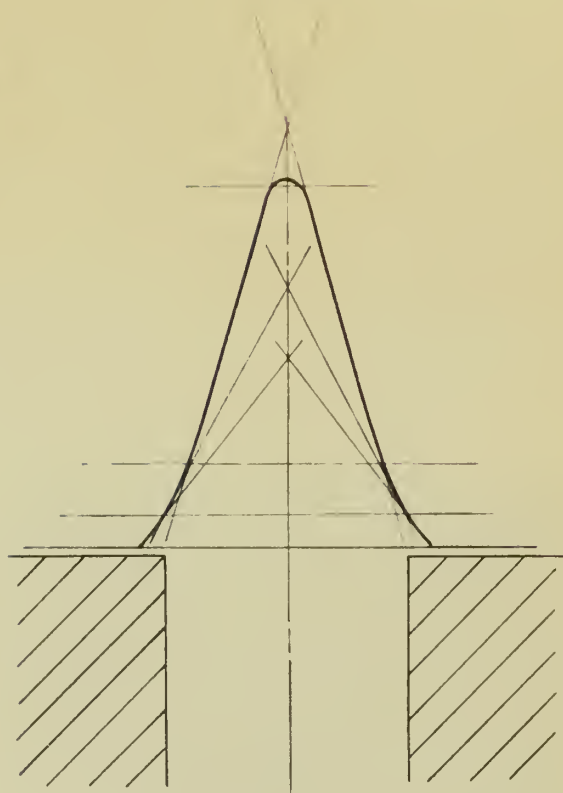


Fig. 4 KINNEY VACUUM PUMP



1.25 Inch Burner Duct

Ethylene - Air

$$\frac{C_2 H_4}{Air} = 0.0846$$

60mm Hg abs.

The area approximation for this example
requires three right circular cone frustums
and one hemispherical cap.

FIG. 5 — A TYPICAL TRACE OF A FLAME INNER CONE
SHOWING SURFACE AREA APPROXIMATIONS

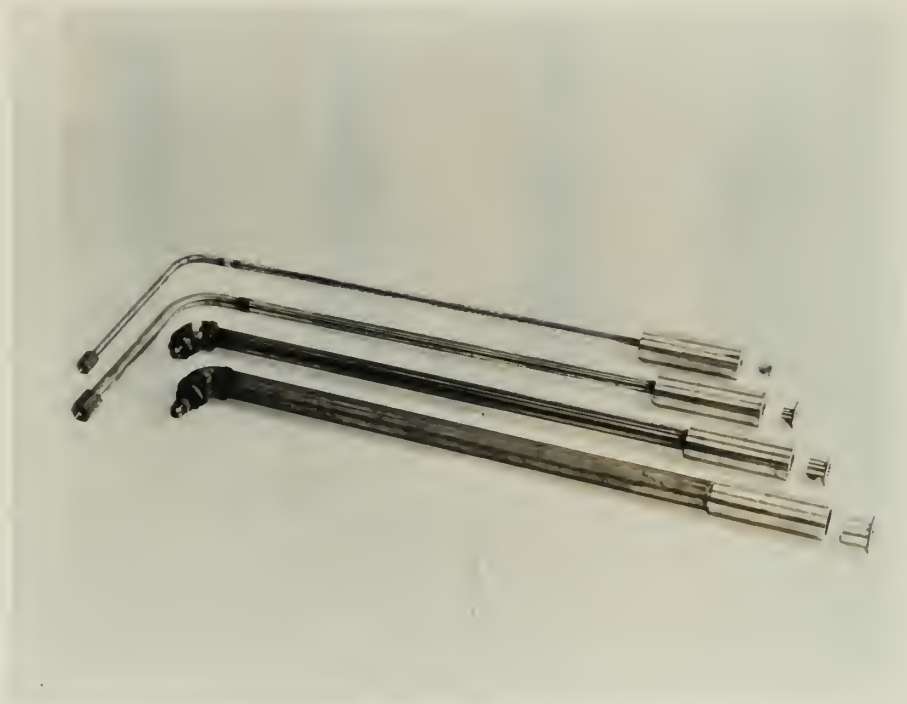


Fig. 6 BURNER DUCTS AND NOZZLE INSERTS

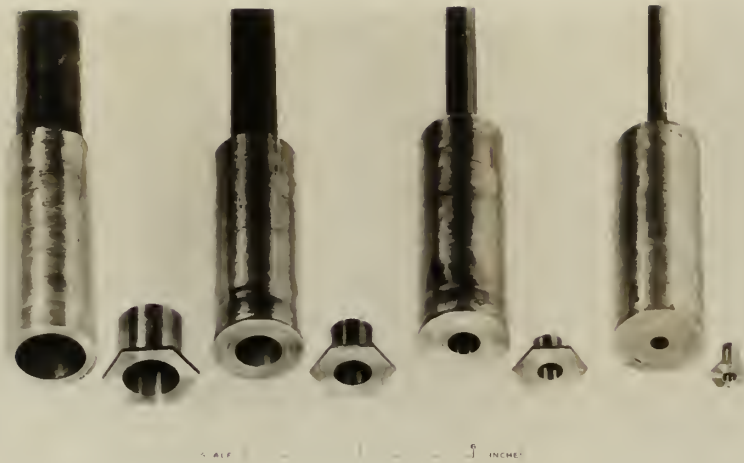
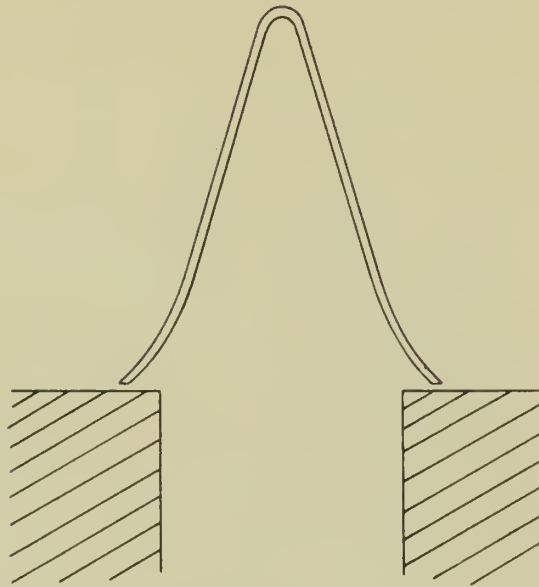


Fig. 7 COMPARISON OF BURNER DIAMETERS



1.25 Inch Burner Duct

Ethylene — Air

$$\frac{\text{C}_2\text{H}_4}{\text{Air}} = 0.0846$$

60 mm Hg abs.

FIG.8 — A TYPICAL FLAME SEATED ON A TYPICAL
BURNER DUCT

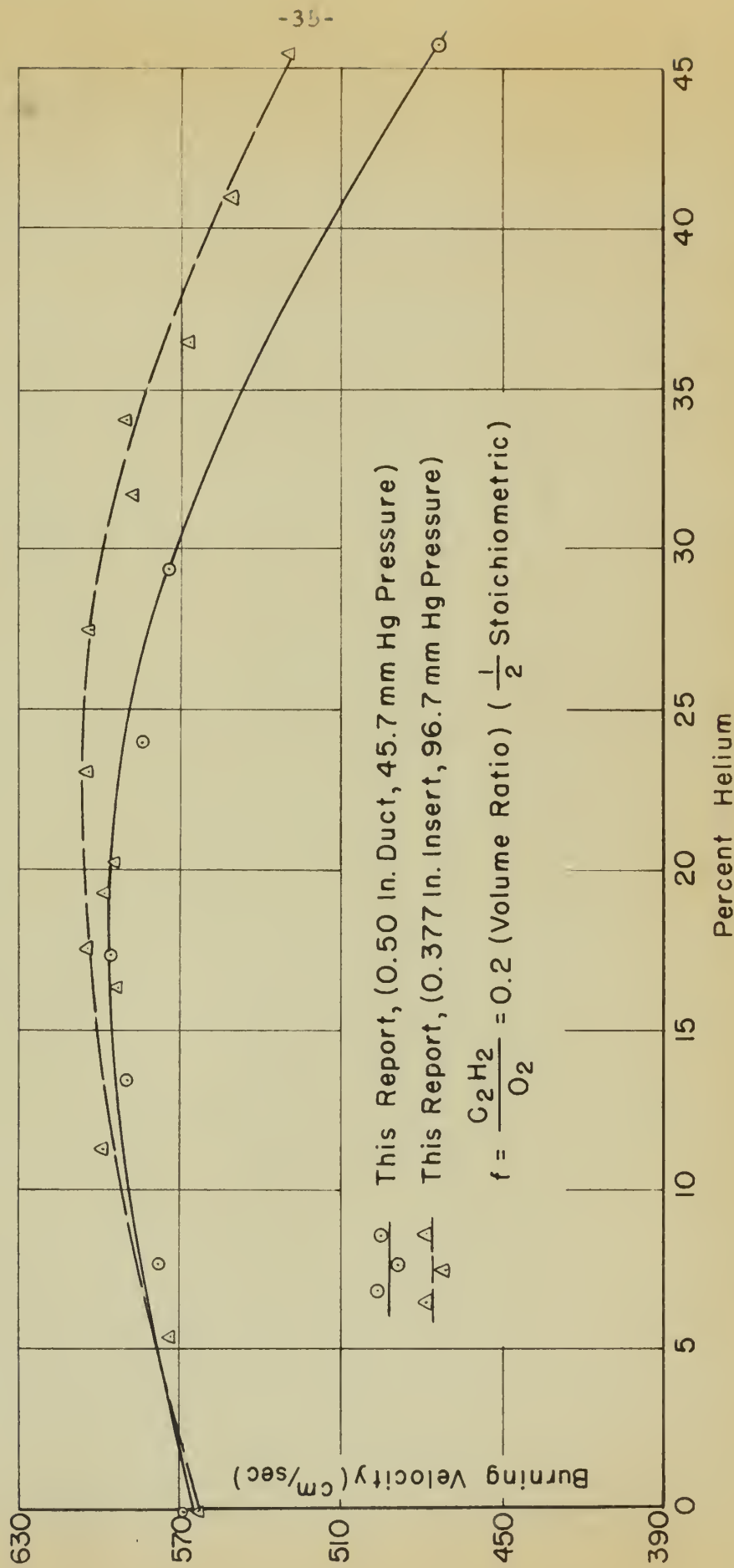


FIG. 9 — VARIATION OF BURNING VELOCITY OF ACETYLENE - OXYGEN WITH ADDITION OF HELIUM

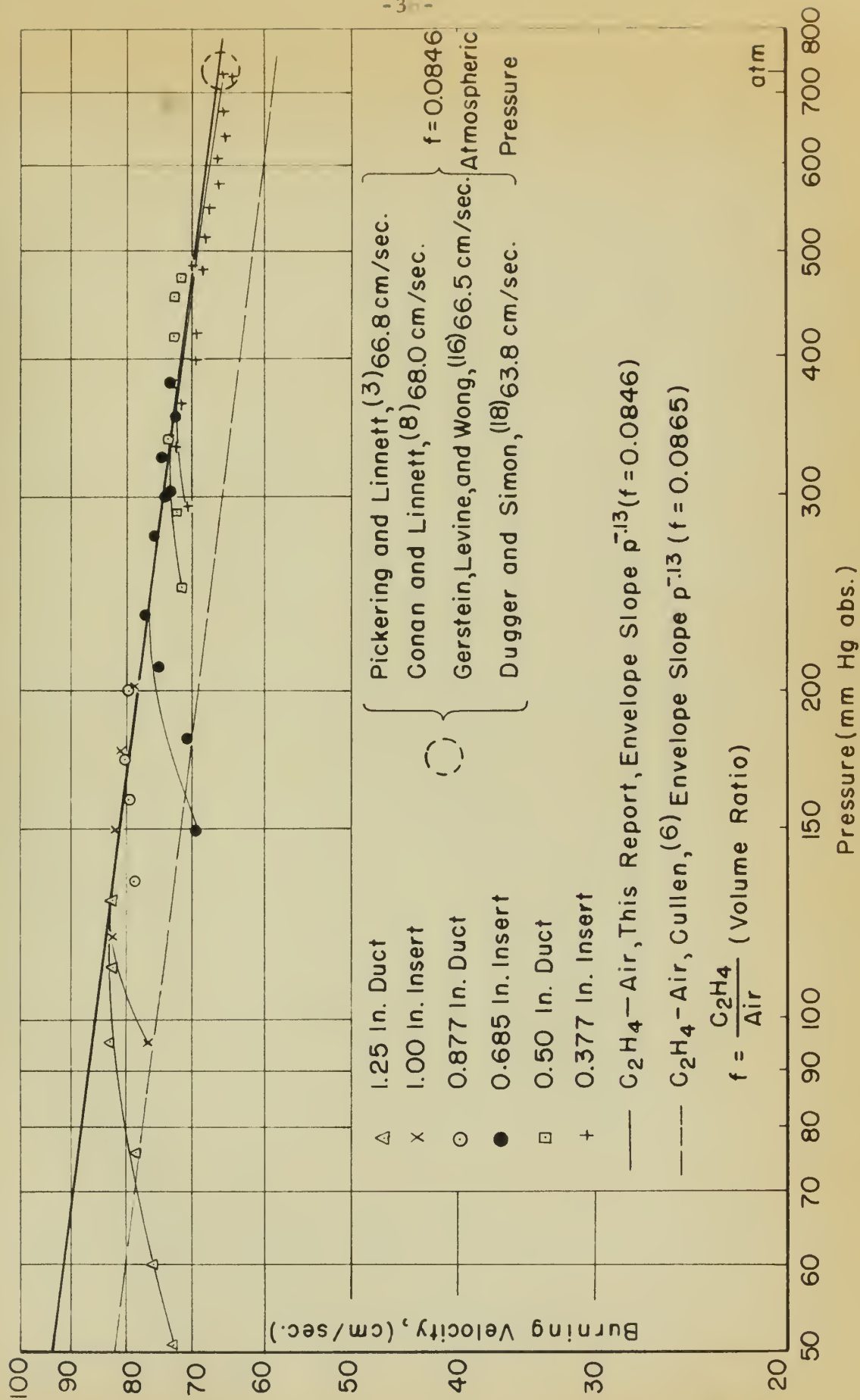


FIG. 10 - ETHYLENE - AIR BURNING VELOCITY VERSUS PRESSURE

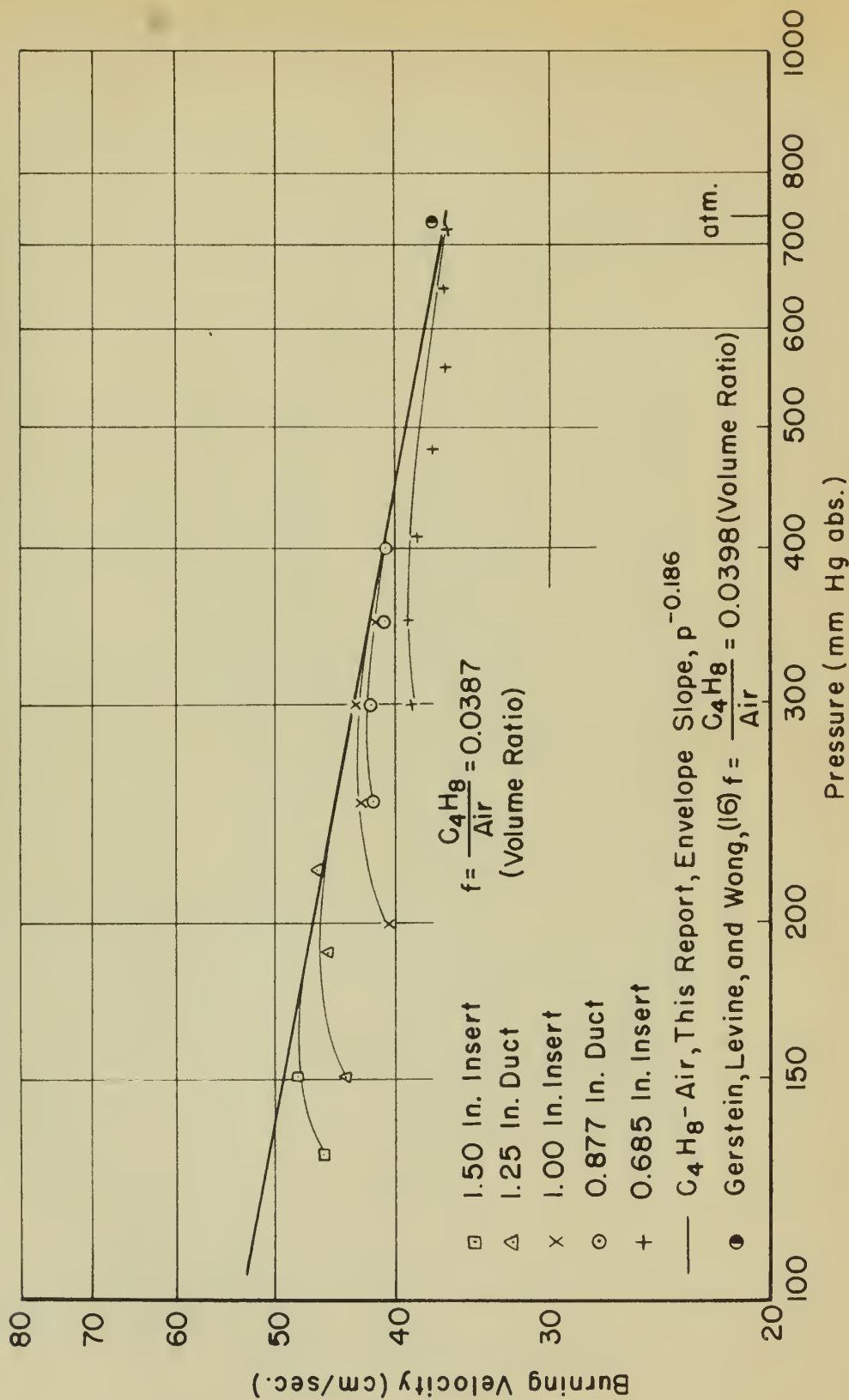


FIG. 11 — ISOBUTYLENE -AIR BURNING VELOCITY VERSUS PRESSURE

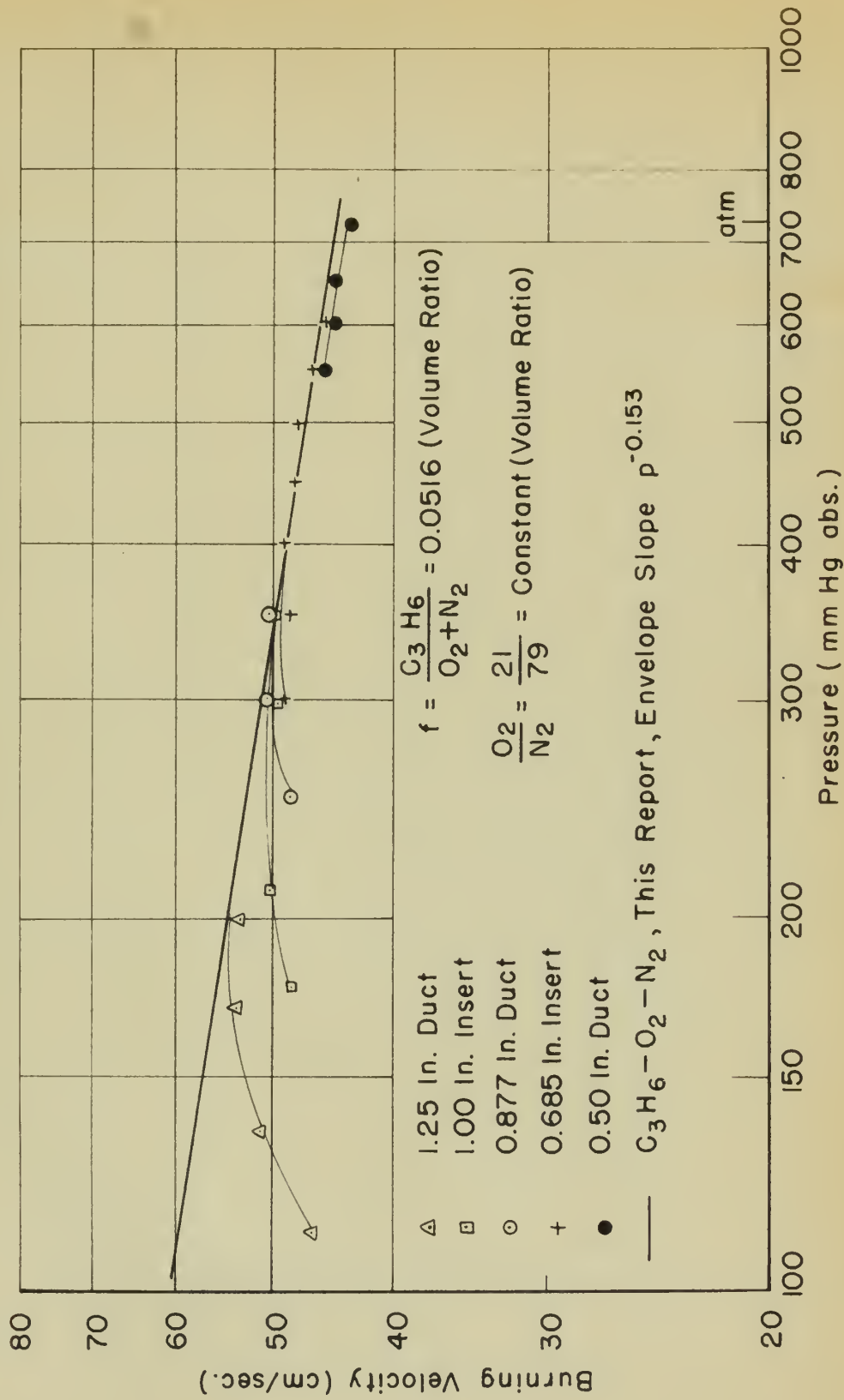


FIG. 12— PROPYLENE - OXYGEN - NITROGEN BURNING VELOCITY VERSUS PRESSURE

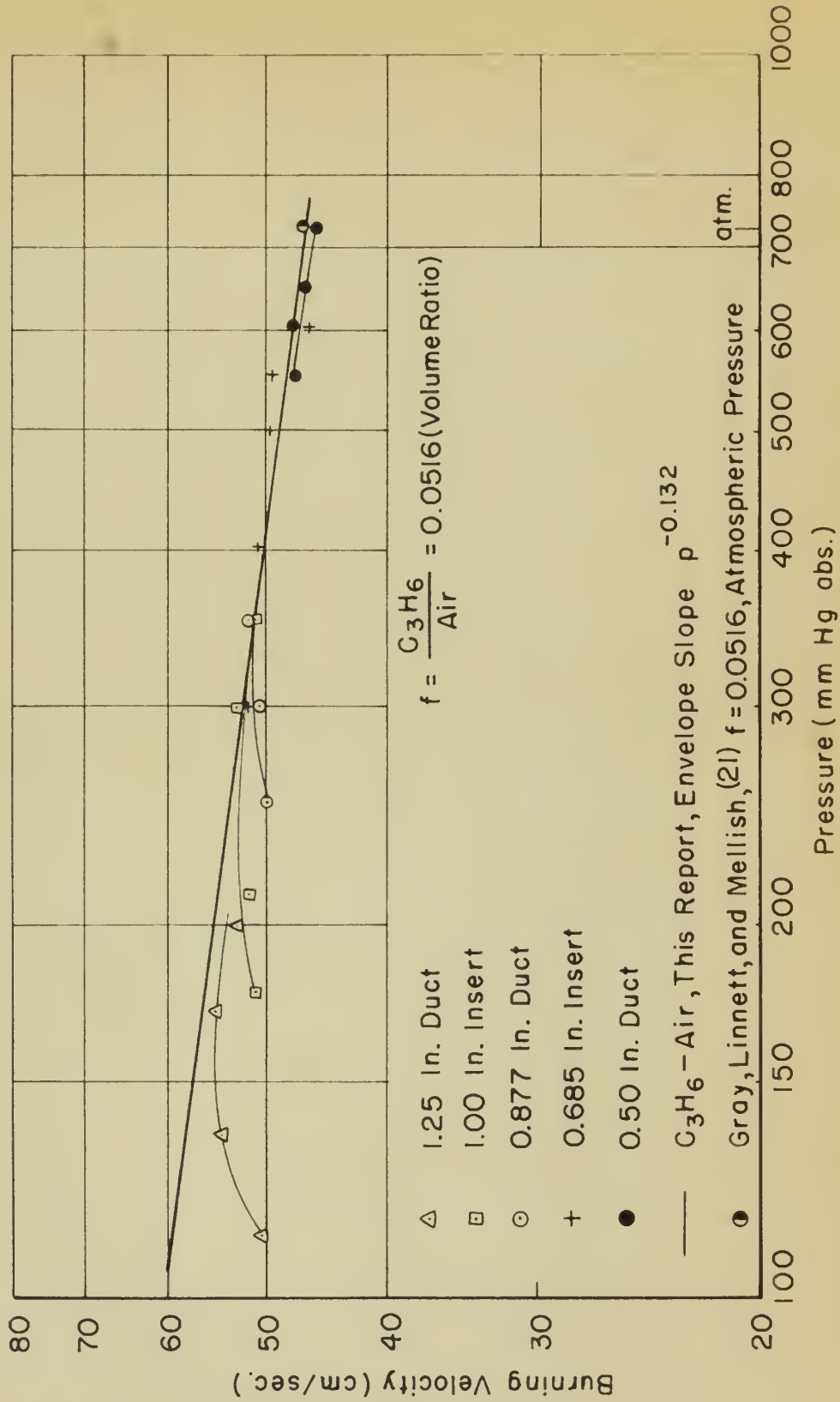


FIG. 13 - PROPYLENE - AIR BURNING VELOCITY VERSUS PRESSURE

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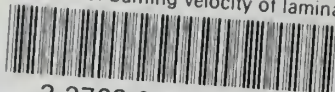
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